Final Report

Continued Operation of the CGPS Network Along the Wasatch Front Region in Utah

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USGS Cooperative Agreement for Regional Geodetic Networks

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Principal Investigator
Robert B. Smith
With Contributions by
Christine Puskas, Jamie Farrell and Wu-Lung Chang

University of Utah
Department of Geology and Geophysics
243 FASB, 115 S 1460 E
Salt Lake City UT 84112
Email: robert.b.smith@utah.edu

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Summary
The University of Utah Wasatch Front, Utah, GPS network is part of the USGS National Earthquake Hazards Reduction Program operating under a Cooperative Agreement for geodetic monitoring of active faults. The principal goal of the Wasatch GPS network is to measure crustal deformation along the populated Wasatch Front, Utah using precision geodetic GPS methodology and to assist in determining the related earthquake hazard. The Wasatch GPS network study area spans the Wasatch and surrounding areas of active faulting in northern and central Utah including the East Great Salt Lake fault, East Cache fault, and the Hansel Valley fault. Primary findings show that the principal deformation pattern for the Wasatch Front is E-W extension as follows (Figures 1, 2, 3): 1) northern Wasatch and surrounding faults up to 2.75 mm/yr., 2) central Wasatch fault including Salt Lake City, 2.35 mm/yr.; and the southern Wasatch fault, at 2.75 mm/yr. The improved analysis and longer period of recording provide higher resolution and more accuracy which suggest there is a better agreement between geodetically determined moment rates that generally agree within the uncertainty of the data (Fig. 5). However the moment rate is still 2.5 times higher than the contemporary seismicity rate. Elastic loading models show that the measured extension is dominated by fault loading on the Wasatch fault modeled as a normal fault in a creeping zone, ~15 km, dipping at ~10-20° W, beneath the rigid elastic and locked upper crustal fault dipping ~55°W (Fig. 6 and 7).

Major Activities of the Geodetic Project:
The University of Utah GPS network deformation project was part of the University of Utah Seismology and Active Tectonics Research Group (UUSATRG), directed by Prof. Robert B. Smith that involved several graduate students and postdoctoral associates. This group provided the key contemporary fault-slip rate data used to evaluate the contemporary fault loading rates and probabilistic earthquake hazard information used by the Working Group on Utah Earthquake Probabilities (WGUEP) throughout this project period (Wong, et al., 2014).

The University of Utah monitors deformation by processing GPS data from 60 permanent GPS stations that include 6 stations operated by the University, 50 stations from the Plate Boundary Observatory (PBO), and 4 stations from the National Geodetic Survey (NGS) (Figure 1). Tables 1, 2, 3 and 4 summarize the Wasatch Front GPS station location, instrument properties, telemetry information, Note that the University of Utah initially installed 12 GPS Wasatch fault stations with USGS support but relinquished operation of 7 stations to PBO. The University of Utah processes all of the Wasatch Front GPS data concurrently with the Bernese 5.0 software. The Bernese 5.0 software was installed on a Dell PowerEdge R410 computer at the Center for High Performance Computing.

The GPS processing was done daily, producing solutions for the position of each station in the network. The solutions are then combined to create station time series (Figures 2a,b) and velocity maps (Figure 3). The data products are posted to the University of Utah Seismology and Active Tectonics Research Group (UUSATRG) web page at http://www.uusatrg.utah.edu.

Data products from the permanent GPS stations are used in probabilistic seismic hazard modeling. The station velocities have been interpolated to velocity fields and strain rate fields for use in geodynamic and kinematic studies of the distribution and magnitude of deformation. Strain rates are converted to equivalent seismic moment rates and compared to historic and geologically determined fault loading rates (Figure 4). The station velocities, when plotted in profile (Figure 5), constrain models of Wasatch fault geometry.

In addition, the UUSATRG worked collaboratively with Dr. Ralph Archuleta, University of California Santa Barbara on a parallel research project focused on dynamic stress modeling of the Wasatch fault where the Utah GPS data were incorporated into parametric models of contemporary fault loading for the stress propagation models.

University of Utah Wasatch Front, UT, Geodetic Project Web Sites:

www.uusatrg.utah.edu/

www.uusatrg.utah.edu/ts_wasa.html

Accomplishments:
Since the start date of the reporting period, our efforts have included:

- Operating and maintaining 6 permanent stations.
- Processing data from 60 University of Utah and PBO GPS stations in the Wasatch Front, Utah.
- Daily transmission of raw GPS data from the University of Utah GPS stations to the UNAVCO archive center, where the data are publicly accessible in near-real time through the web at http://facility.unavco.org/data/gnss/per_sta.php.
- Numerical modeling of the acquired Wasatch fault GPS data and comparison with L. Quaternary fault slip rates and contemporary seismicity rates.
- Participating and presenting our GPS data and results at multiple scientific meetings including, the Working Group on Utah Earthquake Probabilities (WGUEP) meetings, the Basin and Range Province Earthquake Working Group II (BRPEWGII) meetings, and the USGS National Earthquake Hazards Program, National Map coordination meetings.

Data Management Practices:
University of Utah-operated GPS stations record data at 30-second sampling intervals. The data are downloaded hourly and recorded at the University of Utah. The data are also telemetered to the UNAVCO facility, where they are archived in RINEX format. UNAVCO has an open data policy, and continuous GPS data are available to interested users in near-real time via the Internet:

www.unavco.org/data/gps-gnss/data-access-methods/dai2/app/dai2.html#

The University of Utah data are processed using the Bernese GPS engine. Processed data are available online as interpretive-level research products that include station velocity maps and time series available at:

www.uusatrg.utah.edu/ts_wasa.html

www.uusatrg.utah.edu/wasvels.html

Data from our GPS stations are also available to the local surveying community through the UNAVCO website, and data from station RBUT are provided by the National Geodetic Surveys CORS network (http://www.ngs.noaa.gov/CORS/).

Continuity of Operations and Response Planning:
The University of Utah has limited resources for continuity of operations in case of a major

earthquake emergency. Previous proposals included a plan to ensure that data were protected from loss and were accessible if there was an interruption to normal operations. However, this aspect of the project has yet to be funded.

Nonetheless the following items are required to maintain operations:

- Redundant telemetry routing
- More robust power systems for field stations with improved battery and solar panels in case of power interruption

UNAVCO archives the University of Utah RINEX GPS data and PBO processes the data independently, providing some measure of redundancy to the monitoring system, but in case of problems with the telemetry system or stations, there may be a temporary or permanent loss of data. The University of Utah has an uninterruptible power supply but does not back up its data or data products at a remote site, so an event such as an earthquake could potentially cause significant and permanent data loss, as well as loss of hardware and other infrastructure.

We recommend working with USGS NEHRP to develop response plans and obtain technical support for more detailed GPS implementation and upgrading.

Problems or Concerns Encountered

No major logistical or technical problems occurred during the reporting period. There are a number of ongoing minor concerns:

- Maintaining internet access through local providers
- Routine delays in processing site permit requests because of limited resources of the issuing agencies (Forest Service and State of Utah Lands Management)
- Maintaining stations in the mountainous winter environment of the Wasatch Range, with required robust systems and power supplies, and lack of easy access

Other Information and Comments:

The University of Utah is investigating high-rate GPS streaming and near-real time processing. Either of these will require significant changes to processing strategies, but will be important in measuring seismic precursors, co-seismic, and post-seismic deformation.

The University of Utah GPS data have been used or are currently being used in multiple scientific studies by various users:

- Evaluating contemporary loading rates of the Wasatch fault based on the horizontal velocity field and comparing GPS-derived loading rates with historic earthquake rates and paleoseismic determined fault slip rates.
- Examining the variation in horizontal and vertical deformation rates for the footwall and hanging wall of the Wasatch fault, as well as the variations between segments of the fault.
- Comparing the rate of energy release through equivalent seismic moment based on GPS strain rates and earthquake moment rates.
- Analyzing time series and filtering to isolate processing and reference frame anomalies after preprocessing using Kalman filtering.
- Analyzing time series and filtering to evaluate the seasonal hydrologic

component from the long-term tectonic deformation.
- Modeling the fault-loading geometry of the Wasatch fault with GPS measured fault-loading rates.

Collaboration:
The University of Utah Seismology and Active Tectonic group collaborated actively with several organizations including: 1) Dr. Ralph Archuleta and Quinming Liu, Univ. of Calif. Santa Barbara, working on dynamic fault modeling of the Wasatch fault, 2) Utah Geological Survey, working mainly on the projects: Utah Quaternary Fault Parameters Working Group, the Ground Shaking Working Group and the Working Group on Utah Earthquake Probabilities; William Lund, Christopher DuRoss, Michael Hylland, Steve Bowman, and Ivan Wong; and 3) the USGS National Earthquake Hazards Program working with experts on probabilistic seismic hazard assessment including Anthony Crone, Steve Personius, Mark Petersen, David Schwartz, and Nico Luco

Published Papers, Presentation Abstracts, and Meeting Reports of Research Related to this Project

Chang, W. L., R. B. Smith, and C. Puskas, 2013, Effects of lithospheric viscoelastic relaxation on the contemporary deformation following the 1959 Mw 7.3 Hebgen Lake, Montana, earthquake and other areas of the intermountain seismic belt, (in preparation)..

Chang, W., and R. B. Smith, 2011, Elastic and viscoelastic models of crustal motion across the Wasatch fault, II. Models, J. Geophys. Res. (in preparation).

Liu, Q., R. Archuleta, and R. B. Smith, 2012, Curved Fault Dynamic Rupture Study: Wasatch Fault Salt Lake City Segment, Presentation for Utah Ground Shaking Working Group, Salt Lake City, Utah, Feb. 14. 2012.

Pollitz, F. F., McCory, P., Wilson, D., Svarc, J., Puskas, C. and Smith, R.B., 2010, Viscoelastic-cycle model of interseismic deformation in the northwestern United States, Geoph. J. International, v. 181: 2, p. 665 - 696, doi:10.1111/j.1365-246X.2010.04546.

Puskas, C. H., R. B. Smith, W. L. Chang, A. Cannaday and C. DuRoss, 2012, Comparison of Moment Rates from GPS Observations and Late Quaternary Earthquakes on the Wasatch Fault, Utah, Presentation for the Utah Earthquake Working Group, Quaternary Fault Parameters Working Group Annual Meeting, February 2012.

Puskas, C., R. B. Smith, W.L. Chang and J. Farrell, 2010, "A White Paper", GPS research and monitoring of the Yellowstone volcanic system, WY-ID-MT, and the Wasatch fault, UT, University of Utah Seismology and Active Tectonics Research Group, 46pp.

Puskas, C., R. B., Smith, W.L. Chang, G. Blewitt and C. DuRoss, 2015, Kinematics of the Wasatch fault zone, Utah, from GPS measurements, block modeling and fault modeling, in preparation for Geophysical Research Letters.

Smith, R. B., C.M. Puskas, J. Farrell and W.L. Chang, 2012, GPS Monitoring of the Intermountain West for Earthquake-Volcano Hazard Assessment and Research, Association of Engineering Geologists, Annual Meeting Program with Abstracts, p. 79.

Smith, R. B., 2012, Wasatch Front GPS Data Slip Rate Models, USGS Western USA National Seismic Hazard Map (MHMP) GPS Mini-Workshop, September 9, 2012, Hood River, Oregon and Menlo Park, Ca.

Smith, R. B., 2013, Wasatch Front GPS Data Slip Rate Models, USGS Western USA National Seismic Hazard Map (MHMP) GPS Mini-Workshop, Menlo Park, Ca.

Wong, I., Lund, W. DuRoss, C., Thomas, P, Arabasz, W., Crone, A., Hylland, M., Luco, N., Olig, S., Pechmann, J., Personius, S., Petersen, M. Schwartz, D., Smith, R., and Bowman, S., 2014, Earthquake probabilities for the Wasatch Front Region Utah. Idaho and Wyoming, Working Group on Utah Earthquake Probabilities, published by the Utah Geological Survey, August 2014. (note that this reference was included for completeness as it has evolved for several years including the report period here)

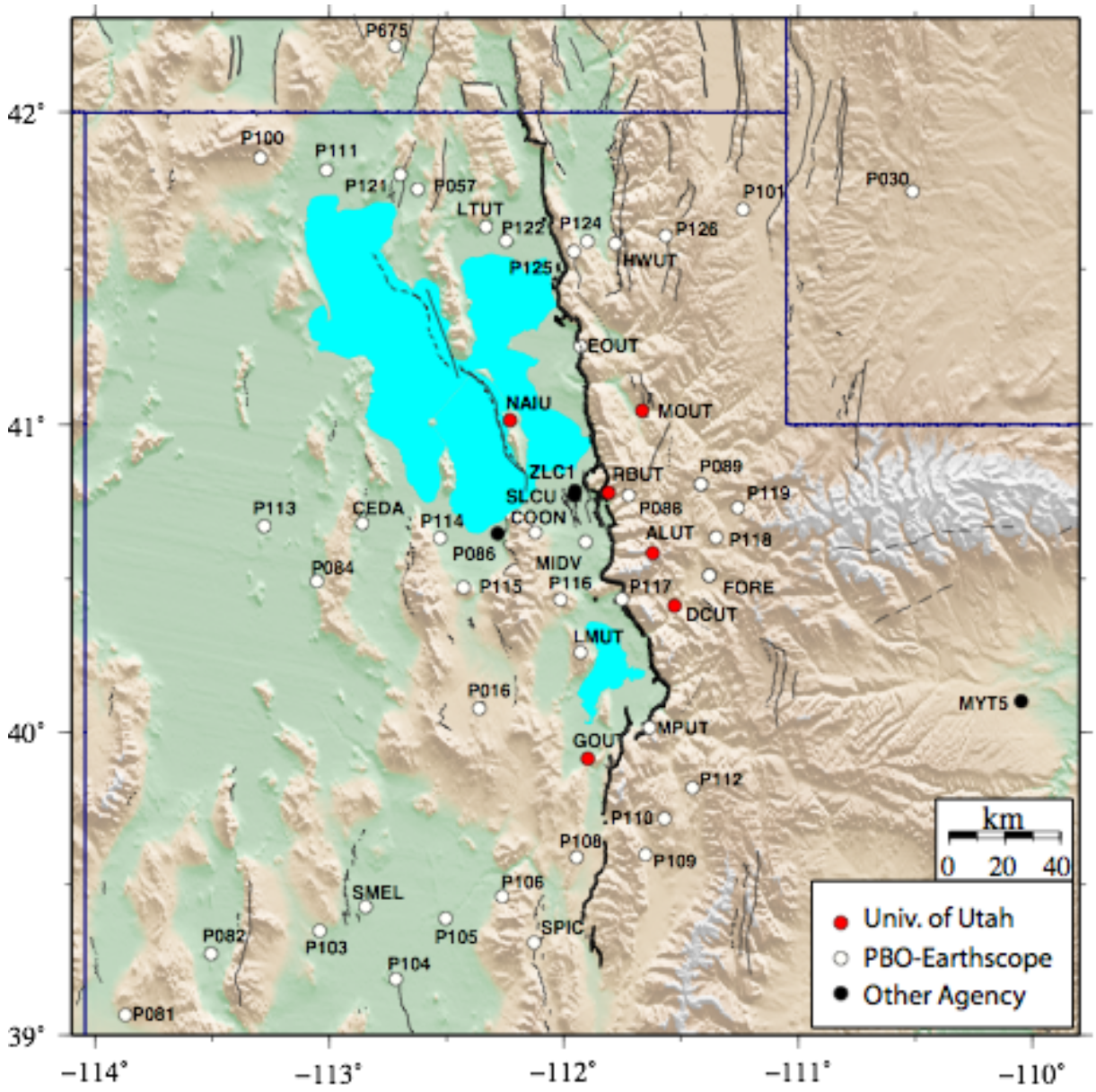


Figure 1. Index map showing the distribution of permanent GPS stations in Utah. Sites operated by the University of Utah are shown in red.

Figure 2: Examples of GPS derived time series across the Wasatch fault in the Brigham City/Weber GPS profile line.

Map includes both University of Utah and PBO permanent GPS stations.

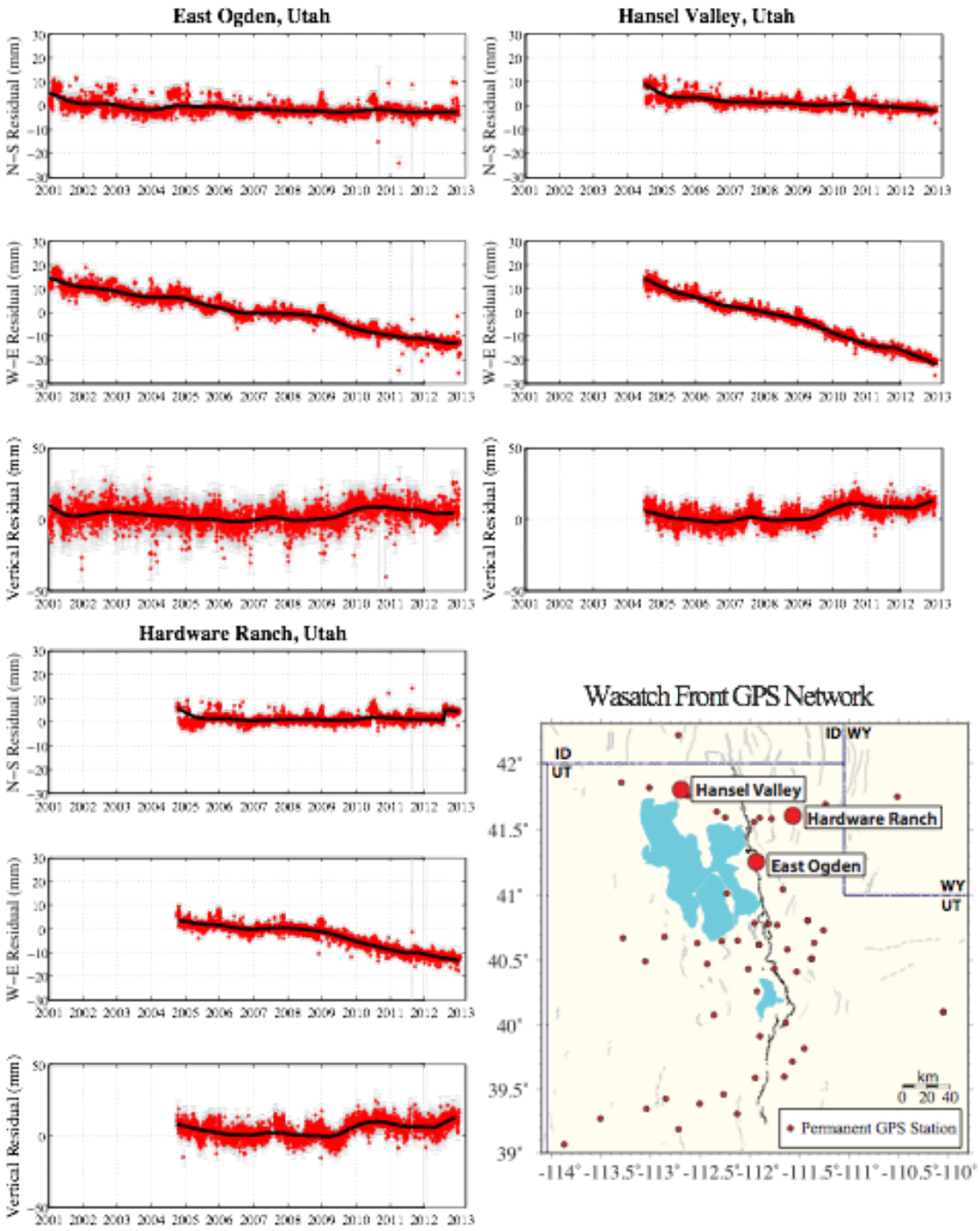


Figure 3: Examples of GPS derived time series across the Wasatch fault in Provo/Nephi GPS profile line.

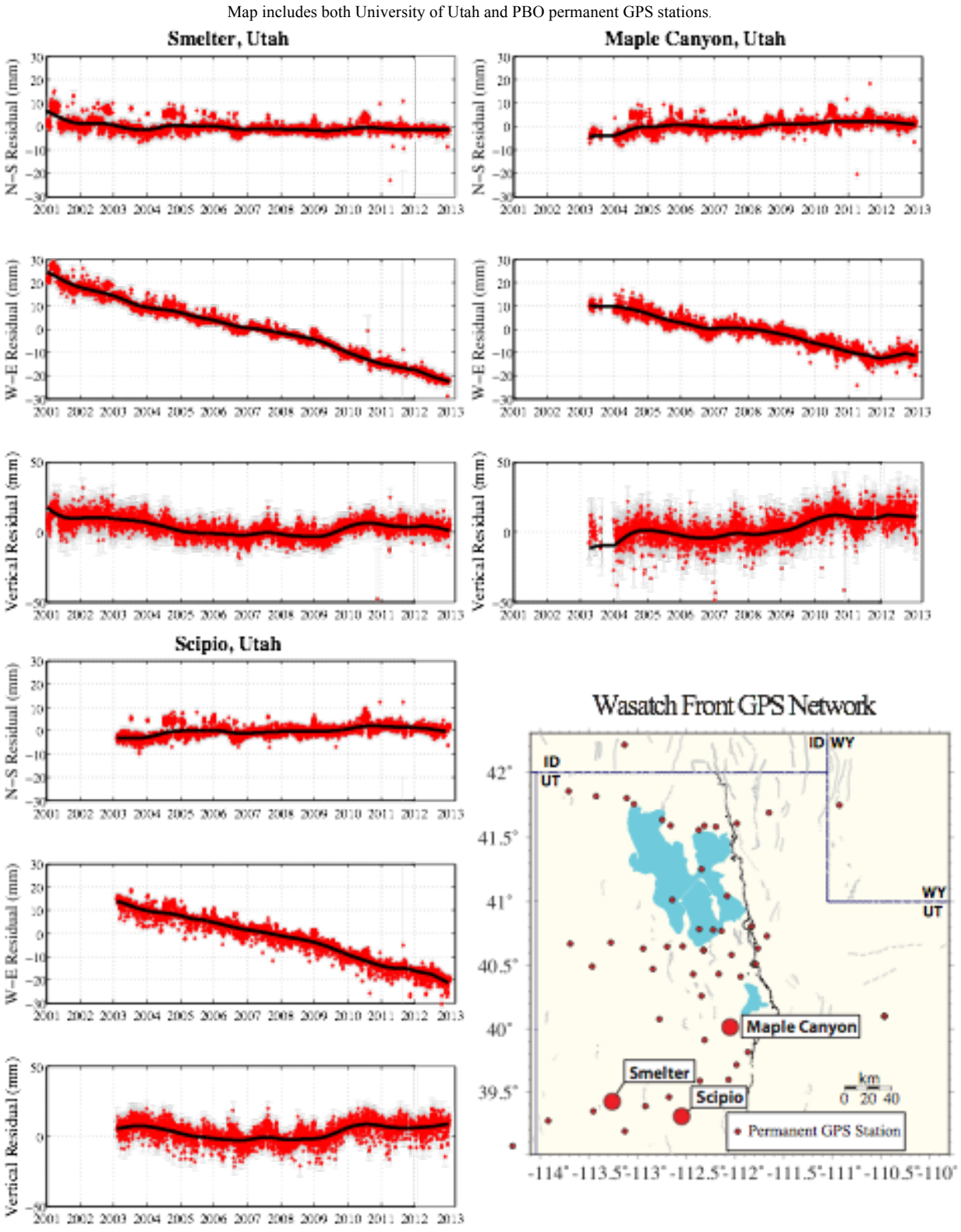


Figure 4: GPS Derived Velocities For The Wasatch Front, Utah
The figure below shows the GPS derived velocities of Wasatch Fault GPS Network. GPS data used for deriving was collected over the time period of April 2005 to March 2013.

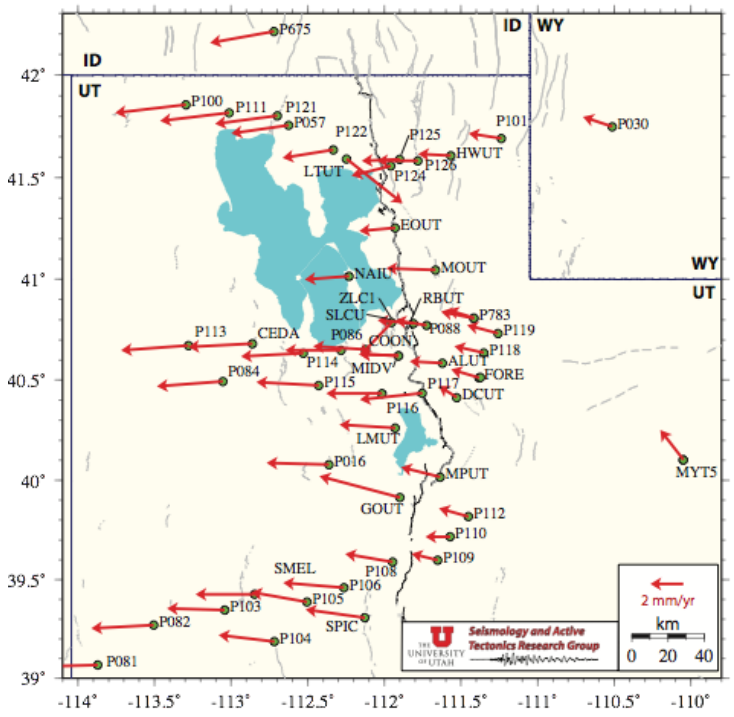


Figure 5: Comparison of GPS Derived Geodetic and Seismic Moment Release Rates
The right side of the figure below shows GPS derived geodetic moment and seismic moment release rates of faults in the north, central, and south areas of the Wasatch Fault GPS Network indicated in the map on the left.

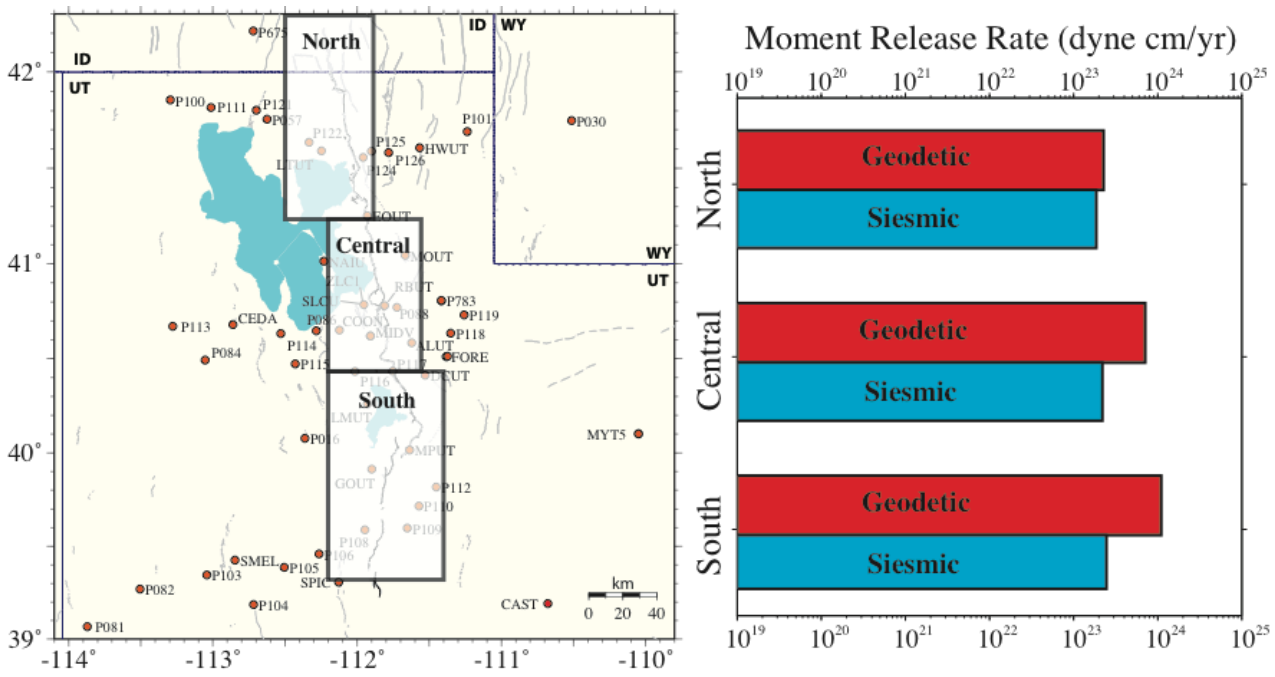
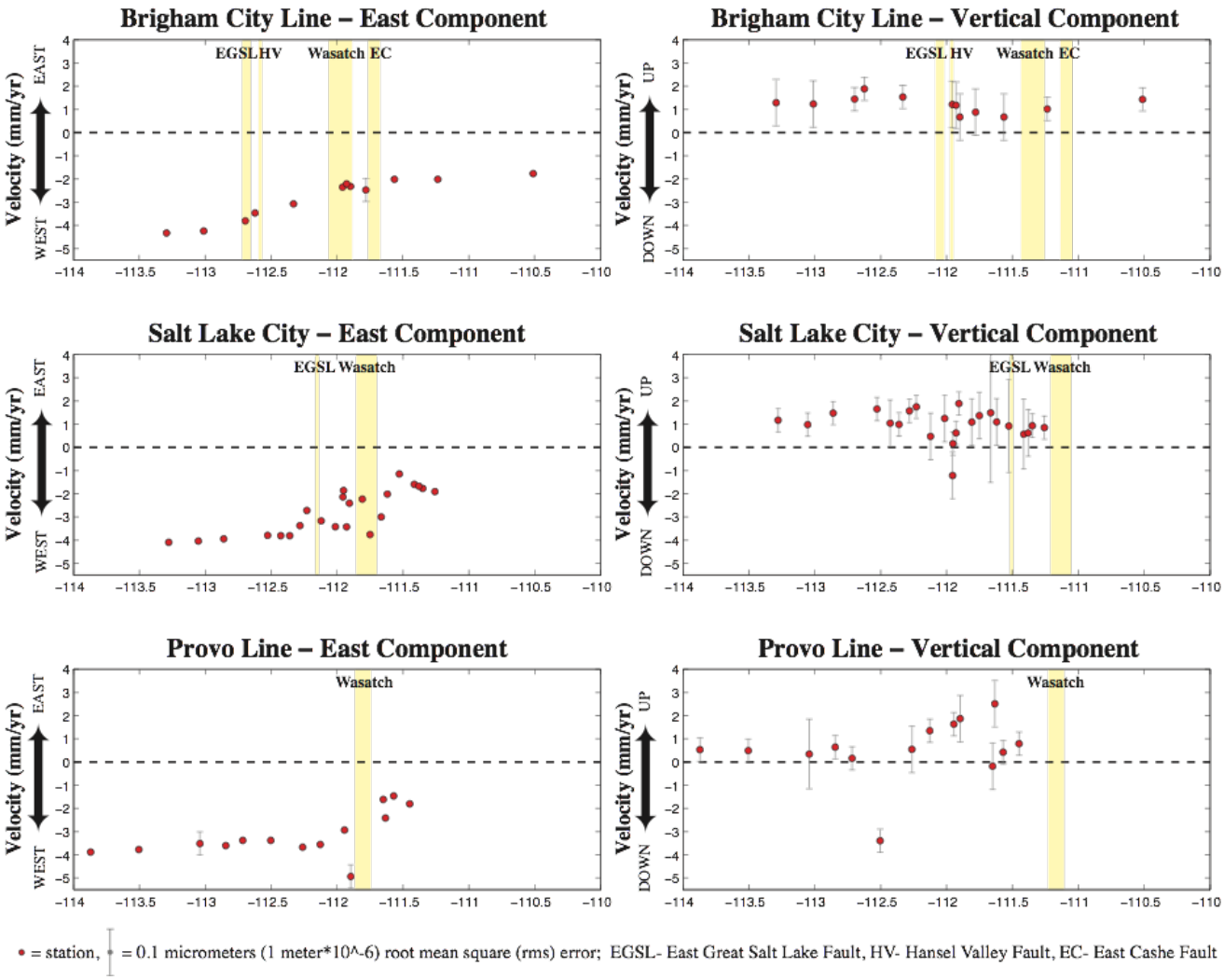


Figure 6: Wasatch Front GPS Derived Crustal Velocity Profiles
The figure below shows is a "snapshot" of the Brigham City, Salt Lake City, and Provo GPS derived velocity profiles, including approximate major fault overlap.



• = station, | = 0.1 micrometers (1 meter*10^-6) root mean square (rms) error; EGSL- East Great Salt Lake Fault, HV- Hansel Valley Fault, EC- East Cashe Fault

Figure 7: Comparison of Wasatch fault geodetic, historical seismicity and Late Quaternary fault slip rates.

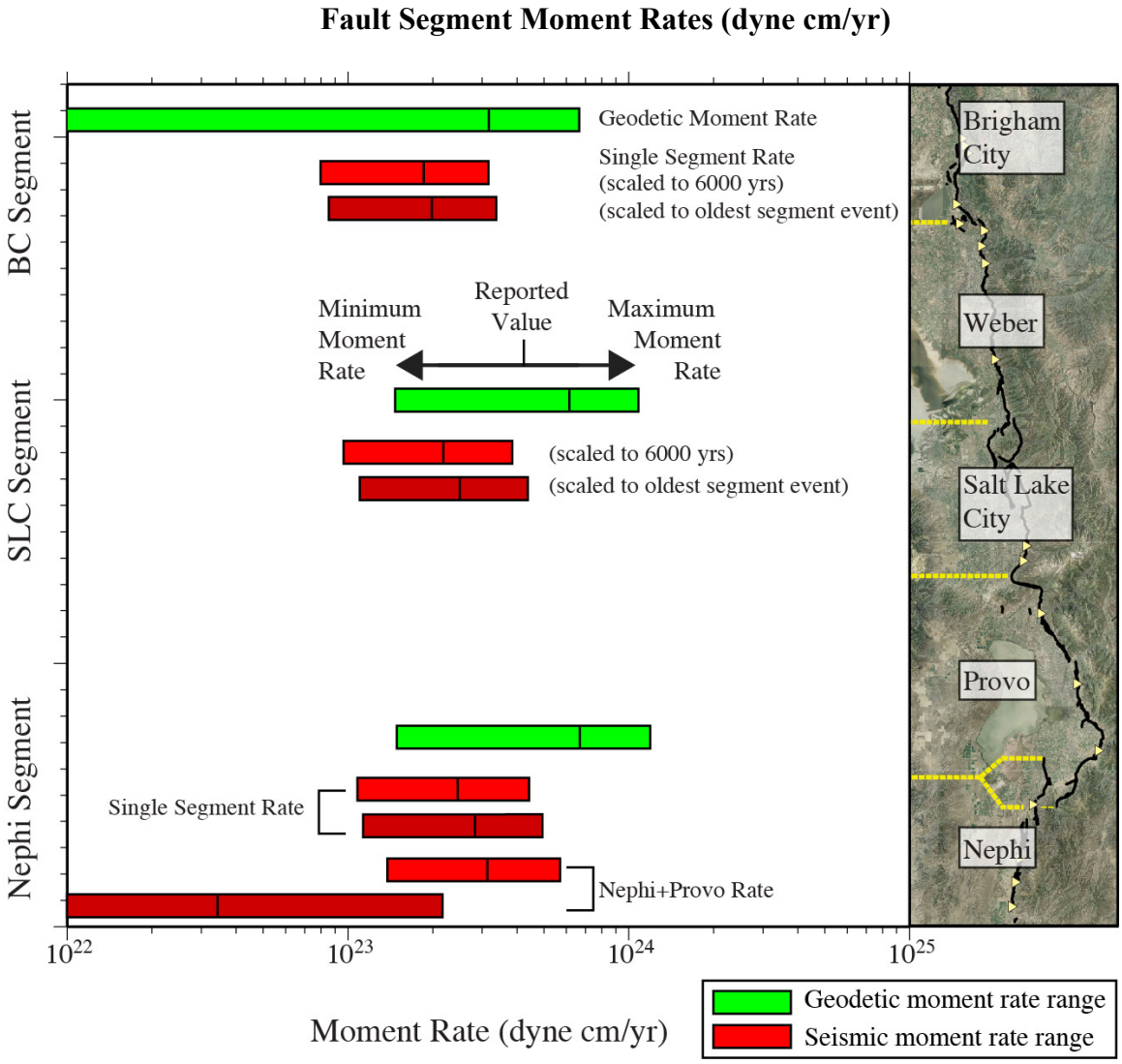


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Table 1 Metadata for Wasatch Front, Utah, GPS Stations

Station Name	Station Code	Site Type	Monument Description	Telemetry	Install date
Alta, UT	**ALUT**	Continuously Operating GPS	Welded to20' ski lift tower	PTP Radio	07/20/05
Deer Creek, UT	**DCUT**	Continuously Operating GPS	shallow foundation pillar	PTP Radio + Cell	10/10/08
Goshen Canyon, UT	**GOUT**	Continuously Operating GPS	shallow foundation pillar	PTMP Radio	09/07/07
Morgan, UT	**MOUT**	Continuously Operating GPS	shallow foundation pillar	PTP Radio	10/17/08
N. Antelope Is., UT	**NAIU**	Continuously Operating GPS	shallow foundation pillar	PTMP Radio	10/14/97
Red Butte, UT	**RBUT**	Continuously Operating GPS	shallow foundation pillar	PTMP Radio	10/1/96

Table 2 Site location information for GPS Utah stations:

City	County	State	X coord., m	Y coord, m	Z coord, m	Latitude, deg N	Longitude, deg E	Elev. m
Alta	Salt Lake	UT	-1788072.11	-4511503.45	4129277.75	40.5839	-111.6200	2824
Heber City	Wasatch	UT	-1785018.74	-4525147.80	4114154.22	40.4137	-111.5270	1796
Goshen	Utah	UT	-1827369.60	-4546524.05	4071612.20	39.9137	-111.8970	1509
Morgan	Utah	UT	-1778927.65	-4478049.22	4167366.38	41.0462	-111.6660	1633
n/a	Davis	UT	-1823707.07	-4462260.66	4164691.98	41.0157	-112.2300	1456
Salt Lake City	Salt Lake	UT	-1797278.94	-4491525.91	4145132.57	40.7811	-111.8088	1668

Table 3 Instrument information for GPS stations, with history of equipment changes.

Station	Date	Receiver type	Receiver S/N	Antenna type	Antenna S/N	Antenna Height, m
ALUT	10/6/2005	TRIMBLE NETRS	4539258391	TRM29659.00	0220335602	0.0
DCUT	10/10/2008	TRIMBLE NETRS	4744140929	TRM29659.00	4624A16995	0.0
GOUT	9/11/2007	TRIMBLE NETRS	4644124599	TRM29659.00	0220335661	0.0
MOUT	10/31/2008	TRIMBLE NETRS	4431236761	TRM29659.00	0220369872	0.0
NAIU	10/15/1997	TRIMBLE 4000 SSI	3615A15272	TRM29659.00	0220075762	0.0

	11/13/2007	TRIMBLE 4000SSI	3615A15268	as above	as above	0.0
	12/12/2008	TRIMBLE NETRS	4646125534	as above	as above	0.0
RBUT	2/24/1997	TRIMBLE 4000SSI	3615A15264	TRM29659.00	0220062078	0.0
	12/12/2008	TRIMBLE NETRS	4435237643	as above	as above	0.0

Table 4 GPS Telemetry information

Station	**Telemetry**	**Sample interval, sec**	**Real time stream available?**
ALUT	PTP Radio + internet	30	no
DCUT	PTP Radio + Cell	30	no
GOUT	PTP Radio + internet	30	no
MOUT	PTP Radio + internet	30	no
NAIU	PTMP Radio	30	no
RBUT	PTMP Radio	30	no